TITLE: A New Technique for Fabricating Three-Dimensional Micro- and Nanostructures of Various Shapes

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A new technique for fabricating three-dimensional micro- and nanostructures of various shapes

V. Ya. Prinz, *D. Grützmacher*, A. Beyer, C. David, B. Ketterer and E. Deccard
Laboratory for Micro- and Nanotechnology, Paul Scherer Institute,
CH-5232 Villigen PSI, Switzerland

Abstract. We have shown that complex 3-dimensional micro- and nanostructures (shells) can be formed by directional rolling up of strained thin heterofilms debonded from the substrate. A technique for controlling the shape and lacation of the structures is proposed and realized.

Introduction

Nanometer-range structures are of great interest since they hold much promise as building blocks for future electronic and mechanical nanodevices. In nanotechnology, molecular-beam epitaxy offers wide possibilities for precise nanostructuring in the growth direction. However, structuring with similar precision in the remaining two dimensions has not yet been achieved: in this respect, capabilities of traditional lithographic methods remain restricted to some tenth parts of nanometer.

Recently, a breakthrough in this direction was made in [1, 2]. The possibilities were shown i) of detaching from substrate atomically smooth heterolayers of nanometer-range thicknesses (by selective etching of sacrificial underlayers contained in the initial structure) and ii) of fabricating from the strained heterofilms thus obtained nanotubes and other nano-objects of cylindrical geometry. It was shown that using self-scrolling process of detached heterofilms it is possible to obtain nanotubes with almost any desired diameter (from 100 μm to 2 nm for InGaAs/GaAs films [1, 2], and to 10 nm for SiGe/Si films [3, 4]).

The present work is aimed to solving another, more difficult problem, namely, the problem of giving a freed atomically smooth nanometer-thick film a more complicated desired shape. In this study, more intricate objects were obtained from Si/GeSi films.

1. Fabrication technique

Figure 1 depicts the self-scrolling process by the example of a strained GeSi/Si heterostructure heavily doped with boron. In this case, the undoped sacrificial layer can be selectively removed by dissolving it in a 3.7% NH_4OH:H_2O solution, the heavily Boron doped Si and GeSi layers remaining nearly intact due to high selectivity of the etching process between heavily and lightly doped layers [3, 4]. Due to high elastic strain in the GeSi/Si system, the freed film starts rolling thus forming a tube, a spiral or a ring.

To transform a plane figure in a three-dimensional shell of a desired shape, it is required to develop a method that would provide a possibility to roll the plain figure, in a controllable manner, in preset directions. Although, to do this, several approaches can be used, on imposing an additional requirement, i.e., applicability of the method to fabricating nanometer-size objects, too evolved variants (such as, e.g., two-level lithography) should be rejected.

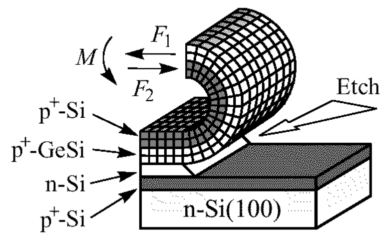

Fig. 1. Schematic view of the self-scrolling mechanism. p^+-Si/GeSi is strained bilayer, n-Si is sacrificial layer. The elastic forces F_1 and F_2 give rise to a moment M of forces which tends to bend the bilayer.

Below, we extend the previously developed nanotube formation technology to fabrication of more complicated three-dimensional objects using a merely geometric approach. The essence of the approach is the following. Obviously, the geometry of the initial plane area determines the sites at which the rolling process is initiated and terminated; this predetermines the rolling directions suitable for rolling more complicated objects. Figure 2 schematically shows initial lithographically obtained plane figures that were used in this study. Apparently, during isotropic lateral selective etching of the underlying sacrificial layer, the acute angles will detach from substrate first, Then, the mechanism of enhanced (by a factor of 1000) etching of the sacrificial layer in the places where the film bends off the substrate starts operating. As the films rolls, access for the etchant to still intact parts of the sacrificial layer opens. This mechanism of enhancement determines directions along which the freed parts of the film roll. The rapid rolling results in formation, in a simplest case, of a ring. On reaching the end of the strip, the rolling processes slows down, thus determining the final position of the resultant three-dimensional shell on the substrate.

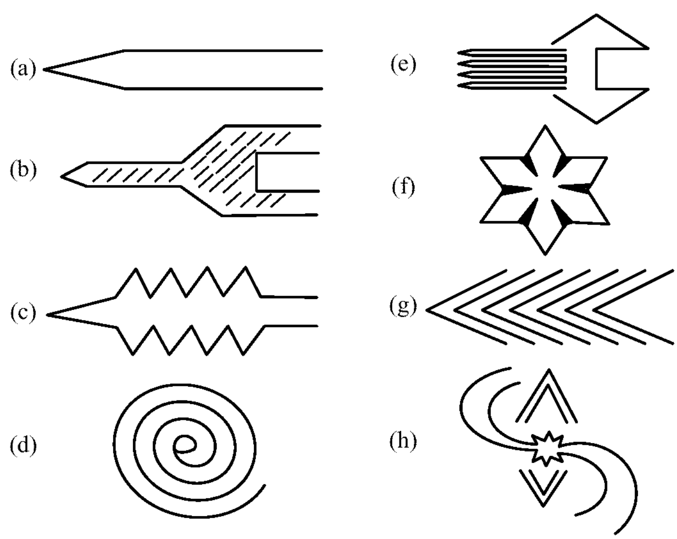

Fig. 2. Simplest patterns formed on strained Si/SiGe heterostructures.

2. Results

Figure 2 shows some examples of simplest patterns that were formed with the help of electron-beam lithography on strained Si/SiGe heterostructures. Regions exposed to the

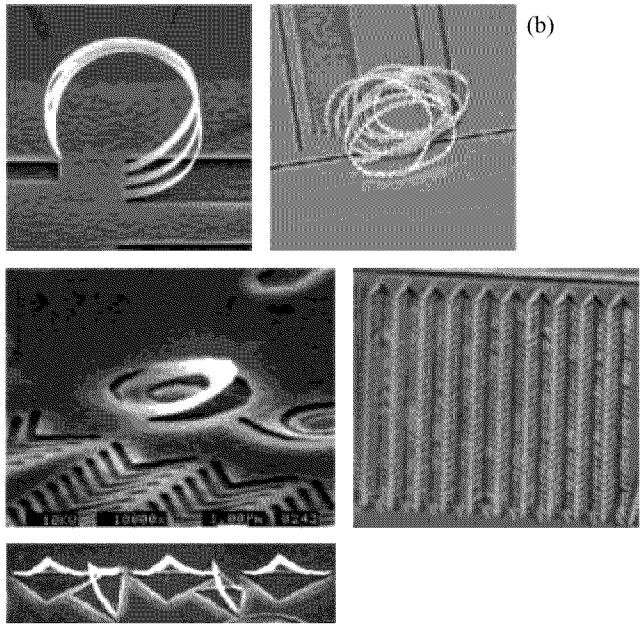

Fig. 3. Open shells formed from bilayer strips of length $L \approx R$, $R = 2\,\mu$m and thickness $d = 35$ nm.

electron beam (seen in the figure as dark parts) were removed by dry etching to locally disclose the undoped-Si sacrificial layer. The experiments were carried out on Si/SiGe heterostructures with the total thickness of bilayer $d = 35$ nm (the equilibrium curvature radius of the relaxed bilayer $R = 2$ μm and also on structures with $d = 6$ nm and $R = 300$ nm. Using these patterns and the above-described directional self-rolling process of the Si/GeSi bilayer, we have fabricated shells of various shapes. Some of these shells are shown in Figs. 3 and 4. Among them are open shells formed from bilayer strips of length $L \approx R$ (Fig. 3), and also closed shells formed from strips with $L \gg R$ (Fig. 4).

Below, open shells are listed which were obtained from the patterns shown in Figs. 2(a)-(h), respectively: (a) strips-needles bent off the surface or directed toward it with their sharp ends (as shown in Fig. 3(a)); (b) a strip-needle bent-off from the substrate upward and aside, which is a result of artificially introduced anisotropy of mechanical properties of the strip (perforation); (c) a sawing (as shown in Fig. 3(b)); (d) a spiral-like strip (Fig. 3(c)).

From pattern shown in Fig. 2(e)-(h) we fabricate shells interacting between themselves: (e) strips-needles directed one toward another; (f) a ball-shaped shell formed by six "petals"; (g) tips (Fig. 3(d)) and an ordered array of needles (which may be used in fabrication of "cold" cathodes) (Fig. 3(e)); (h) a small ball-shaped shell suspended on "pedicles", with two needles attached to it (a useful construction for nanomechanics).

For the case $L \gg R$, the following shells were obtained using the patterns Figs. 2(a)-(f): (a) rings (Fig. 4(a),(b)), a helix (Fig. 4(c)) or tube (Fig. 4(d)); (b) a spiral smoothly passing into a tube at the place where the strip was widening; (c) a tube with modulated wall thickness; (d) rings attached to a tube; (f) six rings (tubes) attached to each other; (g) an array of double (left and right) spirals fixed to substrate with their ends (Fig. 4(e)) (a basic structure for nanomechanics and nanoelectronics devices).

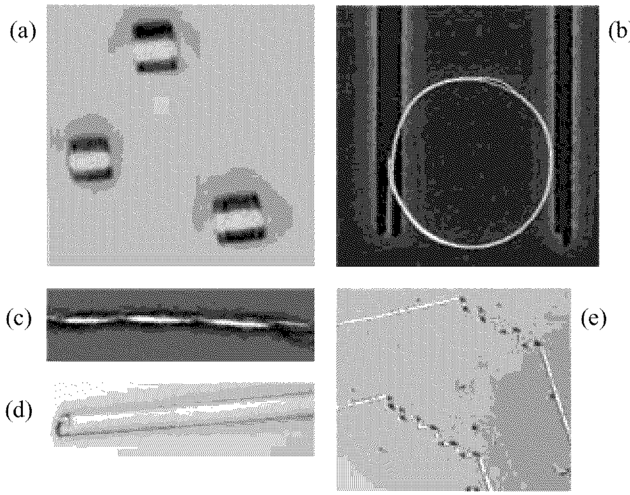

Fig. 4. Shells formed from bilayer strips of length $L \gg R$, $R = 2$ mm and thickness $d = 35$ nm (a,b,d,e), $R = 300$ nm, $d = 6$ nm (c).

3. Conclusion

In conclusion a rich variety of shapes that can be obtained with the above-described technology is noteworthy. In fact, a wide set of plane geometric figures may be transformed into a wide set of three-dimensional shells of various shapes. The simplicity of the method, its applicability to a broad class of materials and, finally, its compatibility with the mature integrated-circuit technology allows us to anticipate its wide practical applications in the future. It is extremely important that, just changing the dimensions of the plane figure to be rolled up in a shell, locally thinning it (by etching) or introducing artificial anisotropy of its mechanical properties, one can obtain a multitude of various shells from identical patterns on one and the same heterostructure. Assembling shells of various shapes into arrays and filling or overgrowing them with various materials, one can fabricate complex architectures the industry requires today.

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